HDR LOS WIRELESS COMMUNICATIONS NETWORK FOR U.S. NAVAL AND MARINE CORPS APPLICATIONS

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ABSTRACT

The government's continuing effort to use Commercial-Off-The-Shelf (COTS) networking and telecommunications hardware and software combined with an increasing desire to extend the reach of voice and tactical internet services is driving the need for high capacity wireless communications systems capable of connecting ships, aircraft, and shore-based platforms. The High-Data-Rate (HDR), Line-of-Sight (LOS), digital network for mobile maritime communications is being designed to provide full mesh, wireless connectivity between members of a Battle Group (BG), Amphibious Readiness Group (ARG), and shore based Marine Corps Command. This paper provides a summary of the wireless networking approaches being considered for the HDR LOS network.

INTRODUCTION

The HDR LOS digital network being considered for development for US Navy and Marine Corps applications has the following requirements [1]. 1) LOS mobile communications between a BG of 6-8 platforms, an ARG of 3-4 platforms, and/or a shore based Marine Corps Command. 2) Full mesh connectivity and adaptable data rates (up to full-duplex T1 per platform) to provide reliable, continuous communication as ship-to-ship/shore ranges fluctuate. 3) Automatic relaying by ships and/or aircraft to extend the LOS network. 4) Network management functions including power control to allow frequency reuse simplifying frequency planning. 5) Support for packet-based services (e.g. TCP/IP), circuit-based services (e.g. point-to-point and point-to-multipoint voice and video teleconferencing), and legacy applications. 6) Rapid implementation using COTS equipment and existing shipboard equipment as possible. 7) The network must support the U.S. Navy's Joint Maritime Communications System (JMCOMS). The following sections describe possible networking approaches and implementation trade-offs for the HDR LOS network. Figure 1 depicts an HDR LOS network made up of eight mobile platforms.

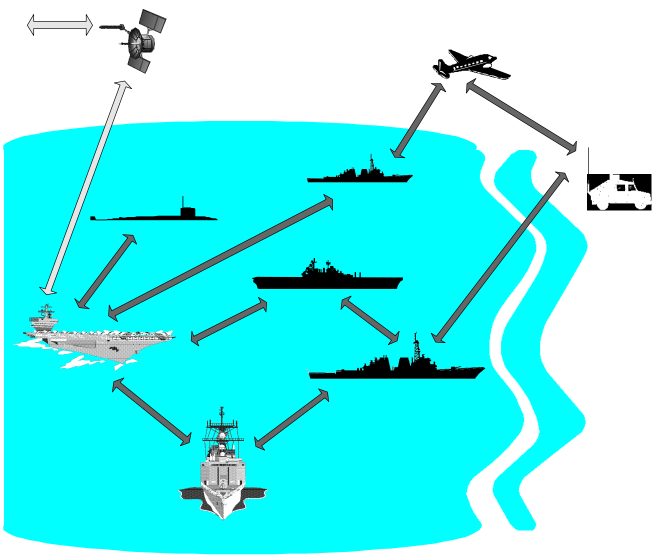

Figure 1. HDR LOS Network Topology

HDR LOS NETWORKING

HDR LOS networking is divided into two parts, *Internetworking* and *Intranetworking*.* Internetworking provides mechanisms for running applications across *heterogeneous* networks. For example, internetworking services make it possible to perform a file transfer between a PC with a dial-up Point-to-Point (PPP) connection through a corporate X.25 Wide Area Network (WAN) and an HP server on an Ethernet LAN. The transport and network protocol layers perform internetworking. For the HDR LOS network, internetworking capabilities provide the mechanism by which user services are supported (TCP/IP, voice, and serial I/O, etc.). The HDR LOS control processor hosts a TCP/IP networking protocol stack to support both the management interface and TCP/IP user applications. In addition to TCP and UDP/IP, the network stack supports ICMP, IGMP, IP unicast and multicast routing, address resolution, SNMP network management, and RSVP resource reservation protocols.

* This discussion assumes a basic understanding of the seven-layer ISO reference model [2]

External interfaces needed to meet HDR LOS requirements are IEEE-802.3 Ethernet, EIA-422/(EIA-449, EIA-530) serial interfaces, and standard Telephony Interface Modules (TIMs) to provide integrated toll-quality voice through the network.

A candidate system architecture that meets HDR LOS digital network requirements and supports the internetwork architecture is shown in Figure 2. COTS equipment, including a 19" rack mountable VME chassis and various embedded cards (i.e., microprocessor, high-speed serial interface, telephony interface, and GPS), is used in order to provide a low cost, supportable system. The VME Bus connects the control processing assembly (i.e., a 68040 processor card), the HDR LOS modem, and various COTS data communications I/O cards.

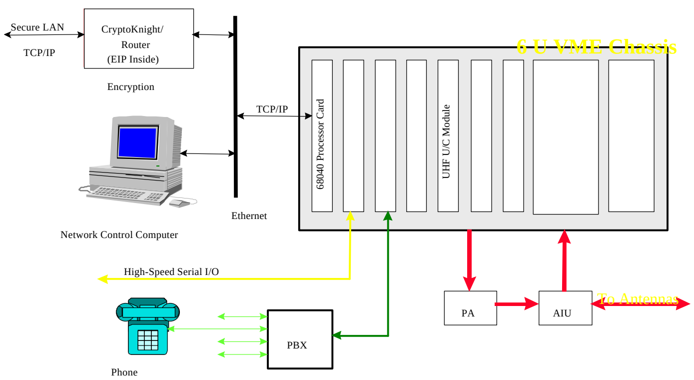

Figure 2. Candidate HDR LOS Hardware Architecture

The control processor manages time critical media access control functions, while the Network Control computer provides network management and user interface. The security architecture requires that users secure data prior to the HDR LOS chassis. For example, the CryptoKnight in-line network encryptor shown above protects the secure LAN. Note that net management functions on the unclassified partition may require TRANSEC cover in the modem.

Intranetworking provides reliable delivery of data between members of a *homogeneous* network (e.g., all computers on an Ethernet LAN). It involves the lower layer protocols: the link layer (commonly referred to the media access layer) and physical layers. In addition, wireless LOS networks define a sub-layer between the link and network layers. This layer, sometimes referred to as Layer 3a, performs intranetwork relaying [3].

To support higher level Internetwork services the link layer provides various delivery mechanisms. These include standard unicast (one-to-one), multicast (one-to-many), neighborcast (one-to-many, no relay), and broadcast (one-to-all) packet delivery; simplex, half-duplex, and full-duplex asymmetric circuits; and combination packet/circuit hybrids. The link layer also supports network initialization, media access control, signal management (i.e., waveform and data rate decisions), frequency management, and power control.

HDR LOS MEDIA ACCESS CONTROL

Of all the intranetworking functions, implementation of the Media Access Control (MAC) protocols has the most significant effect on the capabilities, efficiency, and performance of the network. The MAC algorithms define the low-level interface used to access the HDR LOS network. Both Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) are common MAC protocols for wireless networks. Which MAC approach is best for a given implementation is usually driven by use of existing equipment, bandwidth requirements, protocol complexity, and cost constraints.

FDMA MAC. Frequency Division Multiplexing allows passing multiple, independent signals simultaneously across a single medium by assigning each net member a unique carrier frequency. Assuming a LOS network with four members, each member is assigned its own carrier frequency over which it will transmit data to other network members. Therefore, four carrier frequencies must be assigned to the network. If Node 1 wishes to transmit to Node 4, it transmits via frequency f1. At the same time, Node 4 is always transmitting on f4 and listening to f1 for data from Node 1. The simplest implementation of this approach for a four-node network is for every network node to have one transmitter and three receivers.

The advantage of this approach is that the MAC protocols are fairly simple. Since every net member receives all traffic, data relay is provided by designated relay nodes, which retransmit all traffic to/from relay destinations. Since channel access is not scheduled, channel access latency is near zero providing minimal delay for user services (excluding congestion effects). The primary disadvantage is that the network is not scaleable. To add a network member, you must add a receiver on each platform and allocate an additional carrier frequency. This means the minimum number of radios across all platforms limits the number of members allowed to join the network. Another drawback is if a particular platform has no data to send at a particular moment, the bandwidth on its allocated transmit frequency is wasted. Furthermore, the requirement to change the waveform or data rate on the fly (to support mobility) eliminates many COTS modems.

TDMA MAC. An alternative to the FDMA network is to Time Division Multiplex (TDM) data for several network members onto a single carrier frequency. The carrier is divided into frames and each frame is divided into fixed length time slots. Every net member is assigned a transmit slot and receives on all other slots. This has the same advantage as FDMA in that MAC layer protocols stay simple and all traffic is received by all participants, keeping data relay easy. Additionally, it decreases hardware requirements (i.e., transmitters and receivers) and the number of frequencies required. Further, the number of net members in the network is virtually unlimited. However this is at the expense of increasing channel access latency (which affects user services). For example, in our four-node network example, if we have 100 ms frame times, the worst-case channel access latency is less than a frame (3 slots or 75 ms). The fixed TDMA MAC protocols also have the disadvantage that if a platform has no data to send during its allocated transmit slot the bandwidth is wasted.

Using TDMA, assume you want to add net members but still maintain a minimum data rate per member. The required transmission rate on the single carrier frequency increases as the number of net members increases, thereby decreasing the Eb/No of the channel. The channel data rate increase is $N*R_{min}$ where N is the number of net members and R_{min} is the minimum required data rate. Consider a four-member network with a single transmitter/receiver providing a 1 Mbit connection between members requiring a 4 Mbit overall transmit data rate. Referring to Tables 1 and 2 below, 15 nmi is the maximum allowable range between nodes to sustain communication. Extending this example to eight nodes, the required data rate becomes 8 Mbps, reducing the LOS range even further. Thus the TDMA approach, though appearing to help the scalability problem has its own problems with scalability: when adding network members user rate or LOS range is reduced and channel access latency is increased.

TDM/FDMA MAC. To mitigate the scalability problem, additional radios could be used on each platform with a TDM/FDMA approach. Each member still only has one TX time slot on one carrier frequency across multiple radios, but the number of net members can be increased without affecting user data rate. Ultimately, this has the same scalability drawbacks as FDMA and TDMA. However, with the same complement of equipment from our FDMA example, sixteen network participants can be supported without affecting user data rates or LOS range and keeping a worst case channel access latency of 100 ms. This hybrid approach allows the network designer to balance channel access latency against net member radio equipment requirements or carrier frequencies available.

DAMA. All of the FDMA, TDMA or hybrid schemes described above waste bandwidth when participants have little data to transmit on their assigned frequency or time slot. To handle this drawback Demand Assigned Multiple Access (DAMA) techniques can be employed. DAMA allows bandwidth to be dynamically allocated to network members based on capacity requests. Unused bandwidth is reclaimed at the expense of small management message overhead to support bandwidth allocation. Since typical maritime traffic patterns have unbalanced network loading across platforms, DAMA provides significant overall network performance gains over fixed TDMA or FDMA. DAMA has the drawback that initial channel access latencies are longer than for non-DAMA techniques. For example, a TCP/IP session over our example four node TDM/FDMA network would have a likely worst case initial channel access latency of 400 ms (four frames). But after the channel reservation was created, the worst case channel access latency would be a frame, or 100 ms. Support for LOS relay complicates DAMA to the extent that relayed traffic must be scheduled and provision for relayed orderwire must be built into the protocol. The advantage is end-to-end management of the relayed traffic.

Both distributed and centralized DAMA control algorithms can be employed. With either approach the amount of management information sent across the network is about the same. The trade-off is that distributed algorithms do not depend on participation of a single net member like the centralized control approach at the expense of more algorithm complexity. As an example, any protocol that involves dissemination of data from all network members (like relay/routing or dynamic frequency allocation) has the potential for marginally connected network members to make different decisions than well connected network members. The central controller has the advantage of positive net control avoiding the risks of distributed algorithms not converging to the same solution. For the reasons stated above, the centralized control approach is preferred. To protect against the loss of the network controller, management protocols are required that automatically select an alternate controller and provide for automatic handoff to the alternate controller in case the primary controller fails. A centralized DAMA control approach is discussed below.

In centralized DAMA, network members contend for resources by requesting network access for a specified duration of time. This request is made in the form of a Return Order Wire (ROW) and sent to the designated network controller by the requesting network member. Figure 3 shows a typical ROW burst.

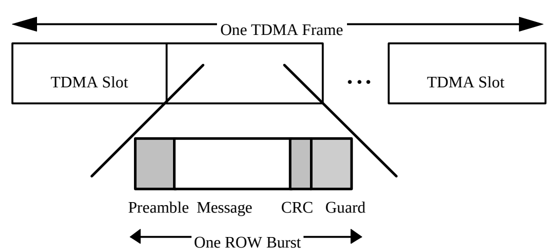

Figure 3. ROW Burst Description

A ROW burst can be transmitted by network terminals in "slotted ALOHA" contention slots. Each ROW burst consists of a preamble for burst acquisition, the ROW message contents (e.g., time critical service requests, answer, relay, and release messages), a Cyclic Redundancy Check (CRC) to verify the integrity of ROW data, and a "guard" time to avoid adjacent slot collisions.

The network controller listens for requests and allocates network resources. At a fixed time during the next frame, it distributes this allocation to the rest of the network in the form of a Forward Order Wire (FOW). Figure 4 shows a typical FOW burst.

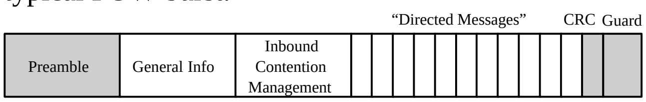

Figure 4. FOW Burst Description

Each FOW burst consists of a preamble for burst acquisition, general net information, inbound contention management data, "directed messages" intended for particular net members, a CRC to verify the integrity of the FOW data, and a guard time. With this type of positive control, transmission rates and slot time duration can be changed for each transmission burst based on measured channel quality, priority, and the amount of data to be sent.

Multi-carrier TDMA DAMA. Yet another networking alternative is to use a *multi-carrier* TDMA modem with DAMA networking. Multi-carrier TDMA DAMA is similar to TDM/FDMA in that it multiplexes data onto multiple carrier frequencies. The advantage is that it goes further in reducing the number of radios needed to support the network. One or possibly two multi-carrier TDMA radios can support the same size network as four TDM/FDMA radios. This gain is realized by adding complexity to the MAC protocol (and the modem). Network TX and RX slot assignments are made with the added restriction that a particular radio (supporting multiple carriers) cannot simultaneously transmit or receive on any of its carriers (though it can operate full duplex simultaneously on different carriers). However, in a LOS network, unused slots due to these restrictions can be used for orderwire relay.

Figure 5 shows a sample time slot diagram for an eight-node multi-carrier TDMA DAMA network. The first time slot on carrier frequency f1 is assigned for FOW messages from the network controller. Therefore, members of the network must listen to f1 during this time to receive the network resource allocation for the next frame. DAMA FOWs, ROWs, and relay slots for FOWs and ROWs are also shown in the figure. The remainder of the frame contains dynamically allocated time slots for data being sent between network members.

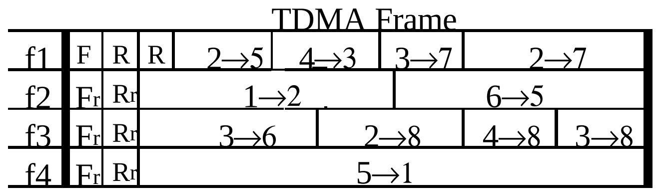

Figure 5. DAMA Time Slot Diagram

Additional Mobility Considerations. Supporting mobility requires active management of the waveform used between platforms. Use of net management protocols allows link quality and network performance information dissemination to all net members. Each member uses this information to perform efficient signal management. Signal management supports automatic detection and correction of effects inherent to mobile LOS networks. Consider the case of platforms moving apart. As the range between platforms increases, the signal to noise ratio (Eb/No) decreases. Transmission signal strength can be increased, but at some point, the Eb/No becomes so small that the bit error rate would increase to unacceptable levels. One way to increase range is to decrease the data rate. This increases the bit time, and therefore Eb/No (for a fixed transmit power) making the signal more visible to the receiver. Table 1 shows the correlation between data rate and range as a function of the Eb/No.

(kbps)	10 nmi	15 nmi	20 nmi	25 nmi	30 nmi
4608	24 (dB)	16 (dB)	8 (dB)	1 (dB)	-6 (dB)
1536	29	21	13	6	-1
576	33	25	17	10	3
64	43	35	27	20	13

Table 1. Maximum Available Eb/No at 100W Tx Power

In addition to changing data rates, changing the waveform modulation can also provide Eb/No gain. Table 2 displays the minimum required Eb/No to support the various modulations.

Waveform	Theoretical (dB)	Typical (dB)
BPSK	10.5	12.0
QPSK rate ½	5.5	6.0
QPSK	10.5	12.5
8-PSK rate 2/3	7.5	9.5
8-PSK	14.0	16.0
16-PSK rate ¾	11.5	14.5
16-PSK	18.0	21.0

Table 2. Minimum Required Eb/No for 10^{-6} BER *

Both approaches can increase range at the expense of channel throughput. The signal management algorithms implemented by the link layer protocol are responsible for determining the most effective and efficient method based upon parameters defined by the network manager.

GENERAL RADIO REQUIREMENTS

* assumes 100 W Tx power

Experiments using existing equipment (with minor modifications) have been conducted to determine the practicality of HDR communications over ship-to-ship and ship-to-shore channels [4]. These tests have shown that the HDR approach is feasible, however improvements are needed in the areas of networking, equipment size/cost reduction, and waveform processing robustness.

The selected waveform and associated processing must be robust to dynamic multipath (flat and selective fading) as evidenced in previous testing. Dual shipboard antennas are anticipated in future deployments to mitigate deep flat fading multipath. Variations in data rate and channelization will be supported through modifications in modem parameters such as constellation format, transmit power, bandwidth, and forward error correction (FEC).

Two different modulation schemes, termed Orthogonal Frequency Division Multiplexed (OFDM) and Single Carrier (SC), are currently being investigated under the HDR LOS program. Each provides a novel method to address channel impairments. OFDM has been investigated for Digital Audio Broadcast (DAB), High Definition Television (HDTV), and high speed cable modem applications. The SC approach has been successfully applied to numerous military and civilian applications including commercial cellular (IS-54, GSM, IS-95) and wireless networking products.

The HDR LOS modem will have a 70 MHz IF interface and be implemented on 6U VME cards using the standard P1/P2 connectors for the data and control interface. The upconverters and downconverters will also be incorporated into the VME chassis. The high power amplifier (100W) may be an external device in ship applications and incorporated into the VME chassis for land mobile applications. General radio requirements to support the HDR LOS network are given below.

- Support operation in the 225-400 MHz band with expandability to other bands (i.e. 1350 – 1850)
- Simultaneous transmit/receive of a full-duplex *n*x64 kbps link using two (one TX, one RX) blocks of *n* 25 KHz-wide contiguous frequency channels. Various channelizations and data rates are specified to support range/bandwidth availability requirements. (T1 or 24 DS0s over a 600 kHz RF channelization)
- LOS range requirements dictate the use of high power amplifiers (approx. 100W). Range of applications dictate operation with relatively linear A/AB amplifiers to smaller more efficient Class C amplifiers
- Support for legacy waveforms (UHF SATCOM is phase noise driver)
- Support for frequency reuse such as TX power control
- Support for variable rates/modulation formats
- Modem supported relay and filtering by address

Efficient DAMA MAC operation also requires variation of modulation and data rate on a burst-to-burst basis and rapid burst acquisition.

CONCLUSION

This paper has described several networking approaches that can be employed for the HDR LOS network. Each approach has strengths and weaknesses to trade off based on the networking requirements. Primarily these trade-offs involve flexibility, scalability, and networking protocol complexity with the FDMA approach on one end of the spectrum and the TDMA Multi-carrier DAMA approach on the other. The selected MAC approach will influence modem requirements and must be considered in the design of the modem and overall network.

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